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REPORT ON THE FINAL PANEL DISCUSSION ON COMPUTATIONAL AEROACOUSTICS

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ABSTRACT

This paper by the Panel Chairman summarises some important conclusions about future prospects for aeroacoustics in general, and for computational aeroacoustics in particular, that were reached in the course of the Final Panel Discussion of the Workshop on Computational Aeroacoustics held from 6 to 9 April 1992 by ICASE and NASA Langley Research Center.

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1. Aeroacoustics at the Start of Its Second Golden Age

In 1992 aviation faces vast new opportunities. Simultaneously, it recognizes environmental responsibilities that are even more exacting than in the past. A new, determined effort to expand aeroacoustics still further is now essential to reconcile shining aviation opportunities with enhanced environmental responsibilities.

For example, the U.S. High Speed Transport Project (HST) aims at achieving big improvements in the economics of supersonic civil transport, which will bring to a wide public the benefits of greatly reduced travel times. Yet its airframe design principles brilliantly minimize levels of supersonic-boom annoyance. Now, the approach to its engine design must be guided by massive aeroacoustic innovation in order to allow HST engine-noise levels to meet the Federal Aviation Agency's "FAR Stage III" goals.

Equally exacting challenges face the developers of new subsonic aircraft (which will, of course, continue to fulfill most of civil aviation's needs) as they plan methods for reducing noise levels of such aircraft to meet "Stage III" requirements, even though thrusts are likely to reach values twice as great as those attained by engines currently in service. If acousticians can rise to this exacting challenge, communities all over the world will benefit from huge shrinkages in aerodynamic-noise "footprints."

The new opportunities and challenges recall to many of us the excitements of the first golden age of aeroacoustics. A brief summary of its achievements, which now follows, may indeed be found instructive.

2. Achievements of the First Golden Age of Aeroacoustics

Fundamental changes in the human condition have resulted from the wide-spread availability of flight at the speeds of jet aircraft. Such aircraft can travel to the farthest place on the earth's surface in less than the time taken for the earth to rotate on its axis. International understanding and cooperation have as result increased immeasurably; for example, current levels of cooperation in Europe would have been impossible if traditional obstacles to such cooperation had not been overcome by airborne vehicles making the Rome-London journey (say) in only two hours.

Yet no such developments would have been possible without the achievements of the first golden age of aeroacoustics. This began when, in the late 1940s, far-seeing sponsors of aeronautical research recognized that the terrifyingly high noise levels of the current small military jet aircraft would need to be greatly reduced if there were to be any chance that the use of much bigger jet aircraft for civil transport might be publicly tolerated. This led in England to an organized research effort by several university groups (at Manchester, Cranfield and Southampton) in cooperation with Rolls-Royce and in correspondence with

parallel U.S. activity based on a group at (the then) Langley Field.

The initial work, involving very close experimental/theoretical collaboration, was directed at understanding the basic science of what we now call “jet noise proper”: the sound radiated from jets in the absence of any interaction of jet turbulence with solid boundaries. A fundamental conclusion of this work was that, for reasons associated with the quadrupole character of such radiation, the acoustic power output varies as $U^8 \ell^2$ for subsonic jets of exit velocity U and diameter ℓ . Yet propulsive power varies as $U^3 \ell^2$; accordingly, it has become possible for jet engines needed in civil aircraft to combine large gains in propulsive power with greatly reduced noise radiation by means of a progressive move towards wide jets of high bypass ratio and relatively low exit velocity².

Later, when jet noise proper had by these means been enormously diminished, a similar effort needed to be put into reduction of aircraft noise from other sources which had by then become relatively more important. These included rotor noise (fan noise from the front of the engine and turbine noise from the rear) and airframe noise from the interaction of boundary-layer turbulence with flexible surfaces, and with control surfaces and flow over trailing edges. Such noise sources are characterized by aeroacoustic theory as combinations of monopoles, dipoles and quadrupoles of well defined strengths, and this analysis proved important for their reduction.

In the meantime, that change in the character of jet noise which is observed as exit speeds rise substantially above the atmospheric sound speed had become understood as a consequence of high-speed convection of aeroacoustic sources producing an effective loss of source “compactness.” Essentially, the radiation changes progressively to one of monopole character; and, thereafter, the acoustic power output varies as $U^3 \ell^2$. It amounts to almost 1% of propulsive power and, at supersonic convection speeds, takes the form of “shocklet” emissions (analogous to supersonic booms) in the Mach direction. Such fundamental understanding was used in the first steps towards reduction of noise from supersonic transport aircraft.

3. The Challenge of Exploiting CFD Advances to Meet Today’s More Exacting Goals

Those enormously more exacting aeroacoustic goals which face the aviation community in 1992 (see §1) call urgently for yet another massively concerted effort. This time, it is the possibility of fully utilizing great recent advances in CFD capability which offers us a

²Initially – that is, before such radically new aero-engine designs could be developed – a similar effect was in part achieved by fitting jet orifices with so-called “silencers” whose essential noise-reducing effect was to promote a massive increase in the rate of entrainment of air into the jet (so as artificially to induce an enhanced bypass ratio).

realistic hope that such an effort may achieve the level of improvement that is demanded both for supersonic and for subsonic aircraft.

Indeed, such approaches are needed even for analyzing how diffraction around a complicated aircraft shape modifies the sound field from aeroacoustic sources; as well as for the refined investigation of noise from those sources themselves whether they be rotors, jets, or airframe boundary layers. We also advocate continued work on “model problems” where methods can be tested and validated through rigorous comparisons with experiment.

For all of the required activity, indeed, it will be essential that, just as the theoreticians of the first golden age of aeroacoustics worked in the closest possible collaboration with experimental scientists, so also the theoreticians of the coming second golden age – notwithstanding their immensely powerful support from modern CFD techniques – should subject their methods to the essential test of experimental validation. All of our recommended programs in Computational Aeroacoustics will need to be pursued, then, in cooperation with meticulous noise measurement programs.

We see two main classes of method as available to the practitioners of Computational Aeroacoustics. The first of these utilizes the characterization of aeroacoustic sources that was developed early in the history of the subject and which is usually described as the Acoustic Analogy; in this method, CFD would be used within the flow itself to evaluate the source strengths, after which simple integrations over the flow field and its boundaries would suffice to determine the acoustic far field. The second class of available methods seeks to apply CFD techniques *comprehensively*; that is, over a much wider region which extends beyond the flow field as such to include at least “the beginnings” of the acoustic far field. We strongly recommend that both classes of method be exhaustively developed, and we see good reasons for expecting that each will be found especially appropriate for certain groups of aeroacoustic problems and relatively less so for other groups.

The original form of the Acoustic Analogy was developed for the purpose of studying the sound radiated from subsonic jets where, as already noted, the aeroacoustic sources are of quadrupole character with enormous disparities in energy level between near-field pressure fluctuations and the very much smaller far-field sound radiation; most of which, moreover, involves wavelengths large compared with typical length-scales in the flow. All of these facts seem to make subsonic jet noise the aeroacoustic problem which is least suitable for treatment by a comprehensive application of CFD throughout the field. Not only would scale separations and energy-level disparities create obvious difficulties in its use but any numerical errors that might effectively introduce spurious sources of monopole or dipole character could seriously distort the inherently less powerful quadrupole radiation.

For subsonic jet noise studies, then, we specifically recommend continued use of the

Acoustic Analogy in one or more of its many available forms. Each of these employs a particular expression for the source strength, preferably chosen so that its values are insignificantly small except in the flow. The classical form T_{ij} of the quadrupole strength satisfies this criterion and, in subsonic jets, has the advantage that its statistics involve length scales comparable with those of the main energy-containing turbulent motions. Alternative forms involving the vorticity are valuable for many aeroacoustical purposes; while, on the other hand, raising some difficulties in jet turbulence because their statistics reflect smaller length scales associated with energy-dissipating motions. In §10 we propose the application of modern CFD methods (including Large Eddy Simulation) to determining the required statistical behavior of T_{ij} in jets. Also, we review the various appropriate types of Green’s function (some based on “the wave equation” and some on certain available alternative forms of linear partial differential equation) by means of which the far-field radiation from those sources may be calculated.

Here, we offer one additional remark that may indeed prove relevant in a wider range of aeroacoustic problems. It is simply that, whenever an acoustic far field has been determined on linear theory, then classical methods are available for “immediately writing down” expressions that correctly describe those gradual modifications to the waveform which result from “nonlinear-acoustics” effects. We strongly recommend that such modifications be routinely calculated; especially, because they involve energy shifts to higher frequency such as may influence “perceived” noise levels (EPNdB).

Out of the above-mentioned group of three serious difficulties for application of CFD techniques “right out to the far field” in estimating subsonic jet noise, all are largely absent in the other principal problems of aeroacoustics; since, for example, the sources assume (§2) a monopole form in supersonic jets while rotor noise involves a mix of monopole, dipole and quadrupole sources. In all of the problems, therefore, we recommend vigorous action to develop effective techniques in *comprehensively* Computational Aeroacoustics, using numerical-analysis philosophies which we now proceed (§4) to outline. Most of the problems, on the other hand, are additionally suited³ to the use of advanced forms of the Acoustic Analogy, and we also strongly recommend in these cases that CFD be actively applied to the improvement of knowledge of aeroacoustic source strengths. The challenging nature of the new demands on aeroacousticians forces us indeed to conclude that they need to be equipped with more than one powerful approach towards the estimation of aerodynamic noise.

³An exception, perhaps, is the problem of diffraction of aeroacoustic sound fields around complicated aircraft shapes.

4. Numerical-Analysis Philosophies for Comprehensively Computational Aeroacoustics

Before sketching specific numerical-analysis principles which are needed in this field of application, we may appropriately emphasize one principle which, in fact, ICASE has consistently espoused in all its work on Computer Applications in Science and Engineering. This is the principle that success in such Applications demands deep, well coordinated thought by human brains working with one or more computers in a very close and effective "symbiosis."

There can, in short, be nothing "mechanical" in the application of computational techniques to difficult problems like those in aeroacoustics. On the contrary, it is essential that powerful intellectual processes (commonly, processes that utilize a vast amount of available analytical information about the anticipated behavior of solutions to problems) be applied in parallel with the numerical analysis, with the computer programming and with the study of computer output.

We shall not repeat this sufficiently obvious and well accepted maxim after thus giving it prominence at the opening of this section. We emphasize however that such a maxim about utilizing to the full intellectual processes based on analytical theories, which may include Acoustic Analogy studies, implies a close coordination between the two "prongs" of that bimodal attack on aeroacoustical problems which we strongly advocate.

It is of course on the solid foundation created by remarkable successes in aeronautical applications of CFD that the relatively new art of comprehensively Computational Aeroacoustics must be firmly based. In particular, some of the necessary techniques can be taken over directly and we stress that this includes the proper handling of boundary conditions at solid surfaces.

The new subject needs, however, to apply a reliable boundary condition at an outer boundary situated (not *too* distantly) within the acoustic far field. Great care is needed to ensure that this is truly a "non-reflecting" boundary condition, and we note that methods derived from the analytic theory of hyperbolic equations (including the mathematical properties of characteristics) can be very effective in achieving this aim.

A feature which even more strongly differentiates Computational Aeroacoustics from classical areas of CFD is, however, the need for a faithful representation of (linear and nonlinear) wave-propagation processes. This becomes increasingly more difficult at shorter and shorter wavelengths, and a realistic approach to the computational problems must, on any given grid, place a lower limit on the wavelengths which the program seeks to resolve. Unless this is done, severe problems including those frequently described as "numerical dispersion" are unavoidable.

A consensus from the Workshop is that such difficulties are best avoided if carefully chosen

“high-order” numerical schemes are applied. Such schemes can avoid numerical dispersion at wavelengths over four times the grid spacing, and they need to be combined with program features that damp out any waves shorter than this.

There is one essentially local exception to the above rule. Long experience with effective CFD codes has shown that well designed codes can reliably locate and characterize shock waves in a flow, but that this is possible only when numerical schemes of very low order are used. This poses the problem of how Computational Aeroacoustics can best handle sound radiation from flows incorporating shock waves.

The answer, as already indicated, is to make a “local exception” in the general neighborhood of any shock waves. Essentially, this means that “high-order” numerical schemes are applied in almost all parts of the flow field, but are caused to give way to schemes of very low order in the neighborhood of shock waves. Experience has shown how carefully compiled codes can successfully achieve this dual objective.

5. Diffraction of Aeroacoustic Radiation around Aircraft Shapes

Because well-established CFD codes used by aircraft companies have, of necessity, acquired impressive capabilities for accurately applying Euler-flow boundary conditions all around a complicated aircraft shape, they form an excellent foundation for codes aimed at solving those diffraction problems that are important in aeroacoustics. These include, for example, the distortion of fan-noise radiation patterns produced by diffraction in the presence of the aircraft shape of the flow around it.

We acclaim the concept of applying (where possible) all the effort that has gone into compiling complicated but effective CFD codes to an important aeroacoustic objective. We confirm, furthermore, that the diffraction problem is just such an objective which, as already noted (§3), cannot in practice be tackled by other methods based on relatively simple Green’s functions.

6. Rotor Noise

In their applications to the rotor-noise problem as such, both of the main approaches (§3) to Computational Aeroacoustics are already flourishing, and firms in both the U.S. and Europe have expressed strong appreciation of what has so far been achieved with these approaches. The field moreover is one where we can predict further exciting and important developments in both methods.

In the Acoustic Analogy approach, precise forms for the surface distribution of monopole and dipole sources associated with moving rotor blades of given shape with specified thickness and loading distributions are well established. The associated “spinning acoustic field”

is readily derived therefrom by surface-integral computations. For high-speed rotors this needs to be supplemented by the field of quadrupole sources associated with important flow features which may include (i) coherent features conveniently estimated in e.g. cascade-type calculations, (ii) shock waves attached to the blades, (iii) incoherent features such as wake turbulence and (iv) effects of blade/vortex interaction. Not all of these features have yet been satisfactorily incorporated in the theories and we recommend an intensification of research aimed at achieving this, research which, needless to say, should use CFD wherever appropriate.

We draw attention also to theoretical approaches utilizing high-blade-number asymptotics. These are important, not because exact numerical evaluation of the necessary integrals poses any severe computational difficulty, but because the asymptotic analysis demonstrates how just a very limited part of the complete domain of integrations generates almost all the radiated sound. This, then, is the region where special effort to estimate flow quantities accurately needs to be made.

Acoustic emission from rotors has also been investigated very successfully by comprehensively Computational Aeroacoustics in certain cases, including the case of helicopter blades without loading. This is a problem where the numerical analysis needs to allow for shock wave formation near the blade tips. Also, codes which allow for large variations in grid spacing are much to be recommended. The method has achieved good agreement with flight tests. It will now be extended to cases with loading; where (once again) it will be important, if possible, to model blade/vortex interaction satisfactorily.

The enormous importance of rotor-noise analysis for future helicopter designs as well as for the development of future advanced turbofan and propfan engines makes it in our view essential to continue to pursue the subject vigorously by means of both the main approaches to Computational Aeroacoustics.

7. Boundary-Layer and Airframe Noise

At the same time we feel strongly that noise originating in airframe boundary layers must not be neglected. Inherently, this is an aeroelastic problem, which involves interactions between boundary-layer turbulence and the flexible solid surface. These interactions are highly relevant to programs of cabin-noise minimization. In some cases, furthermore, mutual excitation between flow fluctuations and aircraft panel vibrations may significantly contribute towards community-noise radiation.

The adequate modelling of boundary-layer turbulence is not just a matter of Large Eddy Simulation. On the contrary, good models must take proper account of the repeated re-energization of the turbulence through “bursts” of intense vorticity emitted from the wall.

Fortunately, some appropriate modelling for this process seems at last to be starting to emerge. Clearly, it will be essential to utilize such models when boundary-layer noise is tackled by Computational Aeroacoustics.

The acoustic interaction of boundary-layer turbulence with a flexible surface is not simple. Radiated noise is known to be almost entirely cancelled in the case of a flat surface of uniform compliance. Accordingly, it may be essential to take into account those nonuniformities of compliance (including concentrations of rigidity) which, while commonly present at the surface of an aircraft structure, can be specifically implicated as sources of boundary-layer noise.

Additionally, as engines are further quieted in the future, airframe noise will be of greater importance. The noise radiated from flow over cavities and struts and the interaction of turbulent boundary layers with trailing edges needs to be moved from the current empirical basis to a more rigorous foundation.

The possibility of “energy-level disparities” resulting from cancellations in the acoustic far field may be thought to suggest that CFD is required primarily to model the turbulence itself, with Acoustic Analogy techniques employed to infer the radiated noise. We remain convinced, on the other hand, that direct Computational Aeroacoustics also needs to be attempted; particularly, for supersonic boundary layers.

8. Model Problems

Precise validation of methodology, especially through rigorous comparisons with experiment, will form an essential foundation for all programs in the second golden age of aeroacoustics. Some essential contributions towards this objective can be made through the meticulous study of so-called “model problems.”

Already, some extremely successful validations of Acoustic Analogy methods have been achieved by the study of radiation emitted when concentrations of vorticity such as vortex rings interact with each other or with solid boundaries. In such an aeroacoustic problem, one of those alternative forms of source strength which involve vorticity (but which may be shown to radiate the same sound field as does the classical quadrupole distribution T_{ij}) can give results in a valuably simple form. The method has been applied using Green’s functions not only for free space but also for various internally bounded regions. In addition, a modified version of the Acoustic Analogy involving “matching” between a near field and a far field has been used successfully.

Each calculation, moreover, has been compared with data obtained in extremely careful experiments, and the confidence of aeroacousticians has been greatly increased by the ensuing demonstrations of gratifyingly close agreement. We strongly recommend continued

work along these lines. In addition, recalling the successes of CFD over many years in evolving good ways of achieving fruitful interactions between computational and experimental activity, we believe that there will be similar benefits to comprehensively Computational Aeroacoustics, with “model problems” providing a substantial proportion of the needed comparisons.

9. Noise from Supersonic Jets

We have emphasized (§3) how effects of the convection of aeroacoustic sources can be described by an analysis which is valid uniformly at all Mach numbers of convection. This requires, essentially, that the finite correlation duration (as well as the finite correlation length) of aeroacoustic sources be taken into account. Then the change in character of jet noise (from quadrupole-type radiation, influenced by Doppler effect, and scaling as U^8 , to monopole-type radiation, predominantly in the Mach direction, and scaling as U^3) can be recognized as a continuous development with increase in the Mach number of convection from low to supersonic values – provided that the supersonic jets are properly expanded.

On the other hand the vital goal of meeting FAR “Stage II” requirements on engine noise from future High Speed Transport aircraft will demand the most precise knowledge possible, both of the nature of disturbances to supersonic jet flows and of the magnitudes of the resulting acoustic radiation. Accordingly, these are issues to which the Workshop has given special attention.

For properly expanded supersonic jets, we are above all concerned with those *disturbances to supersonic mixing regions* whose characteristics have been intensively studied both by theory (which distinguishes between different types of disturbance at lower and at higher supersonic speeds) and by experiment. In every case the radiated sound field is strongly influenced by the Mach number of convection of the disturbances.

We recognize several promising lines of attack on these problems. For round jets, linear stability analysis indicates the forms of disturbances that can grow exponentially with distance from the orifice, and these indications are found to have real value even when disturbance magnitudes are large. In comparing the aeroacoustic importance of different forms, superiority of convection speed may be found to outweigh superiority of growth rate⁴. Some distinctly encouraging comparisons have been made between experimental data and this theoretical approach (where, admittedly, a somewhat arbitrary choice of disturbance magnitude at the orifice needs to be assumed); and these lead us to propose important new extensions

⁴For supersonic convection speed, the acoustic radiation in the Mach direction assumes almost immediately the “saw-tooth” waveform that results from nonlinear-acoustics effects, and it is of course essential to utilize the known propagation characteristics of such closely packed assemblages of conical shock waves when extrapolating noise levels to large disturbances.

of the work in which CFD will play a major role.

For round jets they will include fully nonlinear treatments of the disturbances. At the same time, it will be extremely important to investigate the potential noise-reduction advantages of supersonic jets with other (e.g. elliptical) cross-sections.

Here, CFD can massively contribute to determining the character of disturbances to such non-round supersonic jets, whether by linearized or by fully nonlinear theories. Here as in some other problems we recognize that different alternative ways of deriving the acoustic field (either in a two-stage calculation of Acoustic Analogy type or in a single-stage, comprehensively Computational Aeracoustics program) may be employed.

In addition, we recognize the continuing need for some aeroacoustic research on the noise of underexpanded supersonic jets (even though these may not be relevant in civil-aircraft applications). Here, the pattern of stationary shock waves in the jet has a dominant effect on the noise, whether it assumes the narrow-band form known as “screech” (generated by a well-established feedback mechanism) or a broad-band form of radiation associated with the passage of turbulence through shock waves.

We explicitly suggest as an important “model problem” for experimental validation of CFD approaches (compare §8) the determination of such noise generated when turbulence passes through a shock wave. We confidently expect the resulting knowledge to prove valuable in a wide range of problems. In the meantime, we also recommend further work on the avoidance of “screech,” including possible investigations of “active” control aimed at de-activating the feedback loop.

10. Subsonic Jet Noise

The noise generated by subsonic airjets under laboratory conditions has been exhaustively studied for over forty years, and it may perhaps be questioned whether any intense further effort on this classical problem is required. There is, however, a continued need for further study of the harder problem of noise radiation from the exhausts of real turbofan engines; which, of course, incorporate a hot central core embedded in a much wider jet of cold “bypass” air.

Those reasons (scale separations, energy-level disparities and multipole source character) which for subsonic jets lead us to propose continued use of the Acoustic Analogy in one of its many forms were explained in §3, where some advantages of employing the classical form T_{ij} for the quadrupole strength per unit volume were also noted. For wide jets, however, it is especially important to take into account how the radiation from aeroacoustic sources is refracted by the sheared motion in the jet itself; as can be allowed for differently in different versions of the Acoustic Analogy.

Where this is applied using free-space Green's functions for "the wave equation" itself, it becomes essential to allow for modification of the radiation pattern for the higher-frequency noise (at, say, Strouhal numbers $\omega\ell/U$ greater than unity) by refraction through the sheared flow; with "ray acoustics" typically used to estimate this. Alternatively, there are several good ways of re-formulating the Acoustic Analogy by a different partition of the equations of motion into linear "propagation" terms and nonlinear "source" terms. They are designed as far as possible to take automatic account of aeroacoustic radiation through the sheared jet flow; and they require, of course, application of a different Green's function associated with the new form of the linear side of the equation.

We recommend continued use of both approaches; at the same time, we very specially emphasize the need for research devoted to characteristics of the turbulence in turbofan exhausts, including (above all) the statistical properties of quantities contributing to aeroacoustic source strengths. We look towards modern CFD methods for providing this knowledge; and, taking into account that the statistical characteristics of T_{ij} are known to be dominated by the relatively large (energy-containing) eddies in the turbulence, we are hopeful that one of the available forms of Large Eddy Simulation may help to achieve this. We strongly recommend an attempted application of LES along these lines.

11. A Brief Overview of our Recommendations

A combination of aviation's massive new noise-reduction requirements with great possibilities for fully utilizing modern CFD capabilities allow us confidently to predict a second golden age of aeroacoustics (§1), following by some four decades on the achievements (§2) of the first. Aeroacoustics must now be involved in intimate interactions with CFD (as applied not only to deterministic flows but also to the statistical characteristics of turbulence), while additionally incorporating rigorous comparisons with experiment.

The new Computational Aeroacoustics will press forward in two parallel thrusts, closely coordinated (§3). In one of them, CFD will be used along lines indicated in §§3, 6 and 10 to determine aeroacoustic source strengths, the associated radiation being derived by the Acoustic Analogy approach in one of its forms. In the other, a direct Computational Aeroacoustics will apply CFD techniques along lines indicated in §§3, 4 and 5 over a region extending beyond the flow field so as to include at least the beginnings of the acoustic far field.

There are some particularly important areas of study, including rotor noise (§6), boundary-layer noise (§7) and the noise of supersonic jets (§9), where we strongly recommend the continued use of both methods. On the other hand, important problems of the diffraction of radiation from aeroacoustic sources around complicated aircraft shapes (§5) will require

the use of comprehensively Computational Aeroacoustics, while Acoustic Analogy methods seem better suited (§§3 and 10) to estimating subsonic jet noise. The study of “model” problems (§8) to allow meticulous comparisons with experiment will be valuable in both lines of attack.

For the first time, the ICASE/NASA LaRC Workshop brought together what we may call “a critical mass” of outstandingly qualified persons capable of creating and sustaining that powerful integrated attack on Computational Aeroacoustics which we envision as necessary. It will be vitally important to maintain and still further increase the strength and coherence of this group so as to ensure success in meeting the objectives of the second golden age of aeroacoustics.